MEMS Optical Switches

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Abstract
Leveraging MEMS's inherent advantages such as batch fabrication technique, small size, integratability, and scalability, MEMS is positioned to become the dominant technology in Optical Cross Connect (OXC) switches. MEMS optical switches with complex movable 3D mechanical structures, micro-actuators, and micro-optics can be monolithically integrated on the same substrate by using the matured fabrication process of the Integrated Circuit (IC) industry. In this paper, we report various popular actuating mechanisms, and switch architectures of MEMS optical switches. The basics of surface and bulk micromachining techniques used to fabricate MEMS devices will be reviewed. Examples of 2D and 3D approaches to MEMS optical switches will be described. The pros and cons of the two approaches will be analyzed. In the short term, MEMS-based optical switches seem to have captivated the attention of both the industry and academia. However, there are challenges that threaten the long-term survival of this technology. The problems that remain to be fully addressed will be discussed.

Keywords: MEMS, Micromachines, Microsystems, Optical Cross Connects, Optical Add/Drop Multiplexers, Optical switches.

I. INTRODUCTION

One of the most promising applications of MEMS technology is in optical communication in general and OXC switches in particular. The OXC switches in today's network rely on electronic cores. As port-count and data rates increase, it becomes increasingly difficult for the electronic switch fabrics to meet future demands. It is widely acknowledged that electronic switch fabrics are the bottleneck in tomorrow's communication networks. This bottleneck has stimulated intensive research in developing new, all optical switching technologies to replace the electronic cores. All optical networks offer many advantages compared to conventional optical-to-electronic and electronic-to-optical networks, including cost-effectiveness, immunity from electromagnetic interference, bit-rate/protocol transparency, and ability to implement Wavelength-Division-Multiplexing (WDM) with relative ease. Therefore, it is desirable to manipulate the data-network at the optical level with optical switches. The optic switches are used to reconfigure/restore the network, increase its reliability, and/or acts as the Optical Add/Drop Multiplexer (OADM). There are, indeed, many technologies competing to replace the current electronic switch fabrics. A successful optical switching technology will have to demonstrate superiority in the areas of scalability, insertion loss, Polarization Dependent Loss (PDL), wavelength dependency, small size, low cost, crosstalk, switching speed, manufacturability, serviceability and long term reliability. Conventional mechanical switches, which are based on macroscopic bulk optics, utilize the advantages of free-space optics; however, they suffer from large size, large mass, and slow switching time. On the other hand, guided-wave solid-state switches have yet to show great potential because their high losses and high crosstalk limit their scalability. The recent development of free-space optical MicroElectroMechanical Systems (MEMS) technology has shown superior performance for this application. MEMS optical switches not only retained their conventional counterparts' advantages of free-space optics such as low losses and low crosstalk but also included additional ones such as small size, small mass, and submillisecond switching time. Furthermore, MEMS fabrication techniques allow integration of micro-optics, micro-actuators, complex micro-mechanical structures and possibly microelectronics on the same substrate to realize integrated microsystems.

II. MICROMACHINING TECHNIQUES

MEMS fabrication techniques utilize the mature fabrication technology of the Integrated Circuit (IC) industry. The fact that silicon is the primary substrate material used in the IC circuitry and that it also exhibits excellent mechanical properties [1] make it the most popular micromachining material. The micro-mechanical structures used in MEMS optical switching can be fabricated using two popular micromachining technologies, bulk micromachining, and surface micromachining.

A. Bulk Micromachining

This is the most mature and simple micromachining technology. Bulk micromachining is sometime called the etching/subtraction process. It involves the removal of silicon from the bulk silicon substrate by etchants. There are two types of chemical etchants, anisotropic and isotropic etchants. Anisotropic etchants etches different silicon orientation planes at different rate. Figure 1a shows the silicon planes exposed by using anisotropic

etchants. Figure 1b shows a 3D mechanical structure that was fabricated using anisotropic etching.

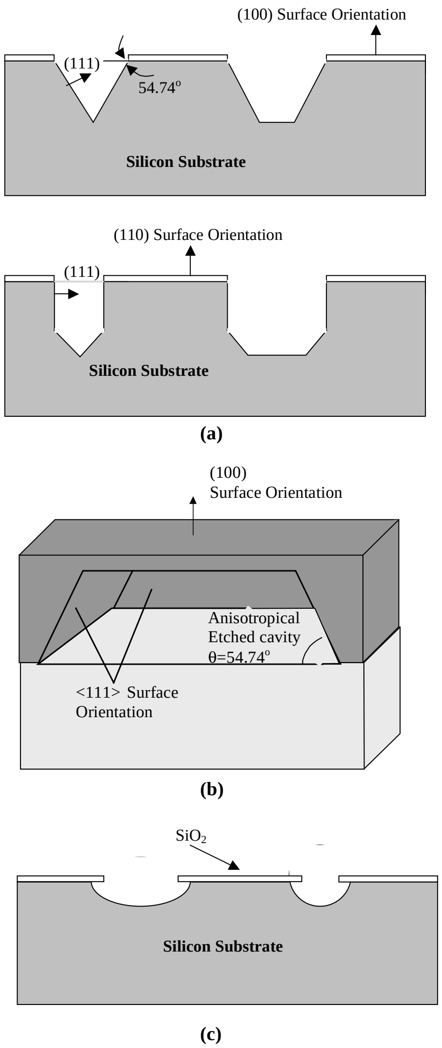

Figure 1. (a) Anisotropic wet etching of (100) and (110) silicon substrate; (b) Deep cavity form in silicon by anisotropic etchants; (c) Isotropic etching of silicon.

Isotropic etchants, on the other hand, etch the silicon evenly in all direction. Figure 1c shows the effect of isotropic etches on silicon substrate. Note that the mechanical structure that can be created by bulk micromachining is not very complex.

B. Surface Micromachining

Surface micromachining is a more advanced fabrication technique. Complex 3D mechanical structures can be created using alternate layers of sacrificial and structural materials. Sacrificial layers act as spacers between structural layers. Free-standing 3D mechanical structures will be formed when the sacrificial layers are etched away during final release. In surface micromachining, thin-film materials are selectively added to or remove from the wafer. Thin-film material deposited where a free-standing mechanical structure is needed is called a sacrificial layer. The material that is left after etching of the underlying sacrificial layer is called the structural material. In surface micromachining, a combination of dry and wet etching, and thin-film deposition are essential processes to realize micromechanical structures on silicon. A sacrificial layer, such as silicon dioxide, are deposited or grown underneath a patterned material for later removal. The removal process is usually done by chemical etching. After the removal of the sacrificial layer, the patterned material is left as thin-film free-standing mechanical structures as they are suspended over the substrate by the thickness of the etched sacrificial layer. Figure 2 shows the surface micromachining process of creating a free-standing mechanical structure. An insulation layer has been deposited on the silicon substrate, followed by deposition of SiO_2 as the sacrificial layer. The structural layer is then deposited on the SiO_2. Openings are etched in the structural layer to expose the sacrificial layer. The underlying sacrificial layer is etched away to release the free-standing structural layer.

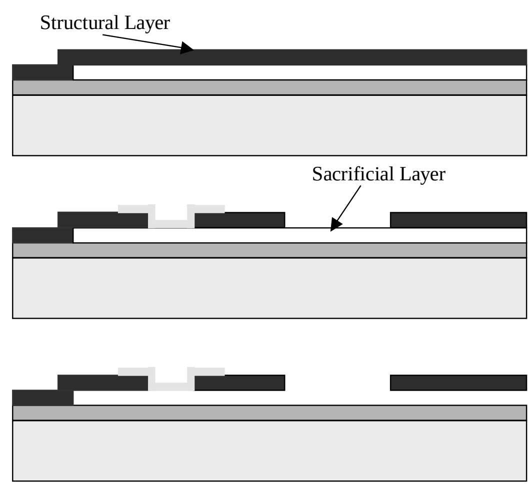

Figure 2. Surface micromachining process where sacrificial layer is first deposited or grown for later removal. In the process, free-standing mechanical structures are released.

III. SWITCH ARCHITECTURES

There are currently two popular approaches to implement MEMS optical switches: (A) 2D MEMS switches; (B) 3D MEMS switches. These two technologies have striking differences in terms of how they are controlled and their ability to redirect light beams. However, both of them have shown promises in finding their niches in telecommunication networks.

A. 2D MEMS switches

In this architecture, mirrors are arranged in a cross-bar configuration as shown in Figure 3. Each mirror has only

two positions and is placed at the intersections of light paths between the input and output ports. They can either be in the "ON" position to reflect light, or in the "OFF" position to let light pass uninterrupted. The binary nature of the mirror positions greatly simplifies the control scheme. Typically, the control circuitry consists of simple transistor-transistor-logic (TTL) gates and appropriate amplifiers to provide adequate voltage levels to actuate mirrors.

For an N×N-port switch, a total of N^2 mirrors is required to implement a strictly non-blocking optical switching fabric. For example a 16×16-port switch will require 256 mirrors. An alternative approach to increasing port-count is to interconnect smaller 2D MEMS switches submodules to form multistage network architecture such as the well-known Clos network. However, this cascaded architecture typically requires up to thousands of complex interconnects between switch submodules, thus decrease serviceability of the overall switching system. In addition, the free-space beam propagation distances among ports-to-ports switching are not constant; therefore, insertion loss due to Guassian beam propagation is not uniform for all ports. The minimum and maximum insertion losses of OMM's 2D 16×16 switching subsystem has a difference of greater than 5dB. 2D optical switches find applications in areas of communication networks, which requires smaller ports sizes.

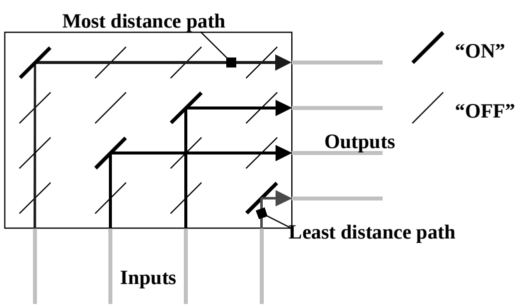

Figure 3. A 2D cross-bar switching architecture.

B. 3D MEMS switches

A 3D or analog MEMS switch has mirrors that can rotate about two axes. Light can be redirected precisely in space to multiple angles – at least as many as the number of inputs. This approach results in only N or 2N mirrors. Currently, majority of the commercial 3D MEMS switch designs use two sets of N mirrors (total of 2N mirrors) to minimize insertion loss. Alternatively, if only N mirrors were used, port-count will be limited by insertion loss that results from finite acceptance angle of fibres/lens. Another advantage is that differences in free-space propagation distances among ports-to-ports switching are much less dependent on the scaling of the port-count. This architecture can be scaled to thousands by thousands of ports with high uniformity in losses. Inevitably, the much more complex switch design and continuous analog control is needed to improve stability and repeatability of the mirror angles. Lucent Technologies announced a 3D OXC using MEMS mirror array called WaveStar™ LambdaRouter [2]. The mirror can rotate on two axes and is controllable continuously to tilt greater than $\pm 6^{o}$. Figure 4 shows the close-up view of WaveStar™ MEMS mirror.

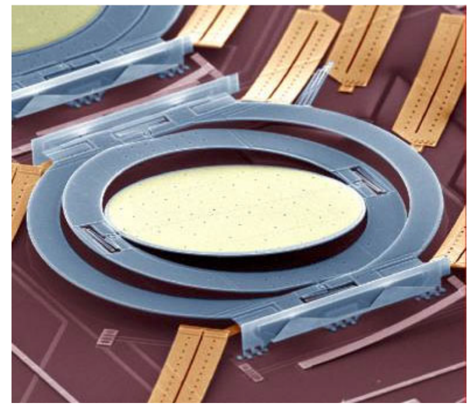

Figure 4. Close up view of WaveStar™MEMS mirror [2].

In the first quarter of 2001, Agere Systems, the former Microelectronics Group of Lucent Technologies, announced a fully integrated, 3D 64×64 MEMS optical switch component that will be marketed to makers of optical networking systems. The 5200 series MEMS switch module is based on the scalable 3D switching architecture developed at Lucent Technologies. Amazingly, the switching module has a maximum insertion loss of 6dB and a switching time of less than 10ms. Another notable development in 3D MEMS optical switch is by Nortel Networks (formerly Xros Inc.). Nortel made headlines at the Optical Fiber Conference (OFC) 2000 by showing the first ever all-optical switch called the X-1000 to beat 1000 port barrier. Following the hype created at OFC 2000, Nortel has recently admitted that only a small portion of the X-1000 actually worked. Nortel's 3D switching architecture is illustrated in Figure 5.

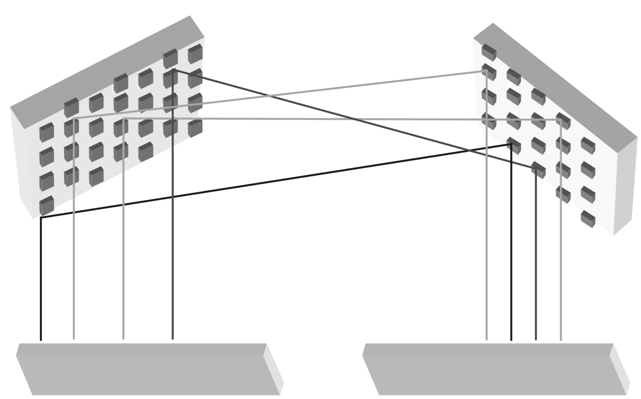

Figure 5. A schematic illustration of Nortel's 3D switching architecture.

Nortel's 3D switching architecture utilizes two sets of N mirrors for a total of 2N mirrors. The first plane of N mirrors redirect light from N input fibres to the second plane of N mirrors. All the mirrors on the second plane are addressable by each mirror on the first plane making non-blocking connections. In turn, mirrors on the second plane can each be actively and precisely controlled to redirect light into desired output fibres with minimum insertion loss.

IV. ACTUATING MECHANISMS

MEMS tilting mirrors alter the free-space propagation of light beams by moving into their propagation paths, thus achieving their switching functionality. In order for MEMS to be a viable optical switching technology, the actuating mechanisms used to move these mirrors must be small, easy to fabricate, accurate, predictable, reliable, and consume low power. This section briefly describes three actuating mechanisms that have been being researched extensively in the university laboratories as well as the industry.

A. Electrostatic

Electrostatic forces involve the attraction forces of two oppositely charged plates. The advantages of electrostatic actuation are that it has a very well researched and understood behaviour. Furthermore, it has very good repeatability, a property that is very important in optical switching. The disadvantages include nonlinearity in force versus voltage relationship, and requirement of high driving voltages to compensate for the low force potential.

The design usually involves mirrors being held in parallel plane ("OFF") to the underlying electrodes. When an electrode is charged at a different voltage level than that of its corresponding mirror, the mirror will be tilted down to its "ON" position and thereby reflects light beam to different output fibre. Toshiyoshi and Fujita of the University of Tokyo demonstrated a 2×2 switching matrix using electrostatic actuation. Optical switching matrix with large isolation of 60dB and small crosstalk of –60dB and insertion loss of 7.66dB are achieved using a bulk micromachined torsion mirror [3]. Figure 6 shows a 2×2 switching matrix with collimated light beams from input collimated beam fibres (CBFs) being reflected off torsion mirrors, fabricated at 45^o to light beams, into receiving CBFs.

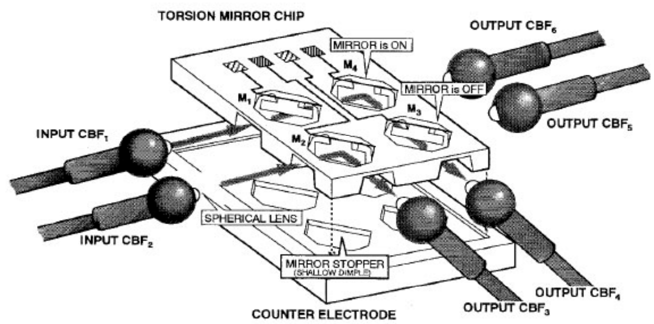

Figure 6. Overall 2×2 optical switching matrix design [3].

One of the leading MEMS optical switching companies, OMM, has already started shipping MEMS switching sub-systems, based on electrostatic actuation, in production quantities since the spring of 2000. 2D switching subsystems of sizes 4×4, 8×8, and 16×16 are hermetically sealed and passed Telcordia Technologies' environmental and reliability requirements for carrier-class equipment. Passing of the stringent Telcordia tests, which include mechanical reliability and endurance, will help to facilitate widespread acceptance of MEMS-based switching subsystems in telecommunication networks. These switches have been used to route live data traffic in an unmanned central office in Oakland, California, with great success. OMM cites insertion loss of more than 6 dB, crosstalk of –50dB, and switching time of 13ms for a 16×16 subsystem.

B. Electromagnetic

Electromagnetic actuation involves attraction between electromagnets with different polarity. The advantages of electromagnetic actuation are that it requires low driving voltages because it can generate large forces with high linearity. Disadvantages such as shielding from other magnetic devices to prevent crosstalk is difficult, and it has yet to prove reliable. The California Institute of Technology has developed a magnetic 2×2 MEMS fibre optical bypass switch [4]. The operation principle of the magnetic MEMS switch is illustrated in Figure 7. The thin double-sided bulk-micromachined mirror moves up or down in response to changing magnetic field. When the mirror moves up, it blocks the optical path to opposing optical fibres. In this case, light signal is reflected off the mirror into neighbouring optical fibres. When the mirror moves down, it moves below the level of the optical fibres, and light signal is transmitted to opposing optical fibres. Electromagnetic actuation can achieve this displacement with less than 100mW.

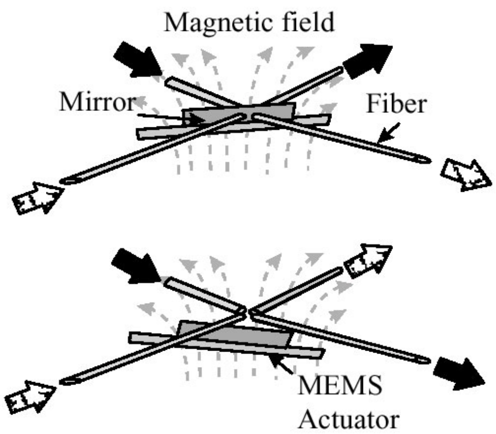

Figure 7. Schematic illustration of operation principle of the 2×2 bypass fibre optic switch [4].

Integrated Micromachines Inc. (IMMI) based in Monrovia, California, has developed a 3D MEMS switching subsystem that has much lower loss than its competitors. It claims an insertion loss of 3dB regardless of switch size. By using electromagnetic actuation instead of the weaker electrostatic actuation, IMMI claims that the driving voltage does not exceed a maximum of 10V. Low power requirement is a critical criterion especially when IMMI is looking to develop the so-called 1000×1000-port monster switching subsystems. Low insertion loss and low power consumption bring benefits on both the system and economical level. Now, less optically efficient but more manageable fibre array connectors can be used, thereby reducing servicing time. In addition, MEMS/CMOS integration, which eliminates tens of thousands of individual mirror control wires, is possible with lower voltage requirements.

C. Scratch Drive Actuators (SDAs)

AT&T research labs have demonstrated an 8×8 Free-Space Micromachined Optical Switches (FS-MOS) for the application of restoration and provisioning in core-transport lightwave networks [5]. The mirror and the Scratch Drive Actuators (SDAs) are monolithically integrated on the silicon substrate using surface micromachining techniques. The rotation of the mirror is achieved by connecting the pushrods with the mirror and the translation plate using micro-hinges [6]. The actuators used are an array of SDAs [7]. The translation movement of the translation plate by the SDA's is converted to a rotation movement of the mirror. Figure 8 shows the complete structural design of the FS-MOS. The length of the pushrod is 75μm, and the distance between the hinges at the bottom of the mirror to hinge joint located on the mirror is 70μm. This design allows the mirror to be rotated up to 45^{o} when the translation plate is moved 2μm, and 90^{o} at a translation distance of 22μm. The number of bias pulses applied to the SDAs determines the plate translation distance, and thus the rotation angle.

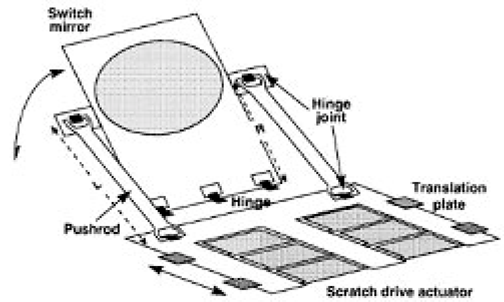

Figure 8. Schematic design of free-rotating fibre optic switch [5].

The optical switch has shown to have a switching time of 700μs for rotating the mirror from an "OFF" position to the "ON" position. Losses measured range from a minimum of 3.1dB to a maximum of 3.9dB. In this design, SDAs have shown to have very fast responses and extremely precise translation movement. With the presence of the pushrod and hinge joints, the mirror can be rotated to multiple angles precisely and reliably, two of the most important requirements of 3D MEMS switches. As discussed in section III(B), the current 3D MEMS switches require the mirrors to be rotated about two axes. Novel designs incorporating SDAs to provide precise positioning of mirrors about two axes of rotation have the potential to reduce needs for complex feedback control electronics.

V. CHALLENGES

In the short-term, MEMS appears to be the forerunner which has the potential to dominate applications including OXC, OADM, and service restoration/protection switches. There remain important issues within MEMS technology that need to be addressed before the widespread acceptance in the core-transport network.

- Reliability

Like any other commercially viable products, MEMS switches should function reliably in changing and often adverse environments. Will the behaviour of the MEMS switches that have been held in the "ON" position for a few months before switching to "OFF" during network restoration/provision be predictable? Or will stiction between materials restrict the movements of the switches? Will switch response times and structural integrity of the optical switches degrade after millions upon millions of switching cycles? Concerns regarding reliability of MEMS-based devices and repeatability in terms of performance need to be well studied in the context of entire optical systems.

- Manufacturability

Characteristics of MEMS-based devices could fluctuate from one batch to the next. Repeatability of material properties and uniformity of processing techniques have to be improved to fully address these concerns. MEMS/CMOS fabrication processes have to be made compatible. The control electronics and wiring schemes can be fabricated in sync with MEMS components thereby eliminates costly hybrid integrations. Researches into novel materials and fabricating processes must be ongoing. MEMS should be driven by technology as well as basic science.

- Serviceability

Matrices of micro-mirrors are fabricated using batch fabrication technique. Will the failure of a single mirror require the replacement of the entire optical switch? Although the inclusion of redundancy in the optical switches will alleviate the problem, it remains to be fully explored.

- Scalability

The ability to incorporate more port-counts when needed is the number one concern of carriers. The increasing amount of data traffic in communication networks, especially for long-distance carriers, will demand even more wavelengths to be deployed. Therefore, optical switches need the capability to scale in order to manipulate the increased number of wavelengths. MEMS-based optical switches must incorporate this key feature to gain widespread acceptance of the carriers.

- Standardization

There is a lack of technological compatibility in the MEMS optical switch market. It is shortsighted to rely on a single vendor for MEMS-based optical switches. However, standardization will come with time. Similarly, there should be compatibility in the front-end MEMS fabricating processes. Ultimately, MEMS industry should mimic what the IC industry has done. Fabrication of MEMS/Application Specific Integrated Circuit (ASIC) can be contracted to centralized foundries specializing in making MEMS devices. To achieve this, standardized fabrication processes/libraries must be defined.

- Packaging

MEMS-based optical switches have close interaction with the physical world through their mechanical components. How will optical switches be packaged so as to minimize effects of changing temperature, humidity, vibrations, and other environmental elements? Packaging invariably affects the performance of MEMS devices. Therefore, it should be included in the initial design phase.

- Automation

Assembly of MEMS components, and automatic optoelectronic packaging and performance testing of MEMS devices are crucial to reducing product cost and cycle time while maintaining product quality. Issues such as self-testing, self-assembly and automated packaging remains to be fully explored.

- Competing technologies

MEMS-based optical switches are facing major challenges from other all-optical switch technologies, and the constantly evolving electronics switching systems. The current state-of-the-art electronic switching systems offer 512 2.5-Gbit/s ports for a combined capacity of over 1Tbits/s. It seems that the adoption of optical switching technologies are faced with fierce resistance from electronic switching systems. It should be noted that Lucent’s LambdaRouter have yet to be commercially successful and are constantly being outsold by electronic switching systems such as Ciena’s CoreDirector. Given the current advancement of electronic switching technology, switching technologies such as MEMS will have a lot more to prove before we can enter the era of purely optical switching networks.

VI. CONCLUSION

MEMS optical switches have demonstrated to have lower polarization dependent loss (PDL), bit-rate and protocol independent, lower insertion loss, and lower crosstalk than guided-wave solid-state switches. Their superior low loss performance allows them to be expandable to larger port-counts. When compared to their counterparts, MEMS optical switches are cheaper because of batch fabrication techniques. They are also smaller in size and lighter in mass thus allowing high-density packing on a single silicon substrate. Currently, there are much research interests in integrating micro-optics and electronics components to MEMS devices to realize true integrated optics. Amidst all the hopes and hypes, MEMS-based optical switch has yet to cross major technological hurdles in order to fulfill its potential as the preferred optical switching technology in the long term.

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